NUCLEATE POOL BOILING IN A ACCELERATING SYSTEM

by

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UNITED STATES
NAVAL POSTGRADUATE SCHOOL

THESIS

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ABSTRACT

A centrifuge system was designed and constructed to investigate nucleate pool boiling of water from a mirror finished copper surface. The system was constructed to withstand acceleration force levels up to 1800 g's and to operate at heat fluxes to 200,000 BTU/hr-ft^2.

No nucleate boiling data was taken due to minor experimental difficulties and due to more serious problems that developed with the heater wire and especially with the thermocouple instrumentation. The system was operated to 460 RPM (200 g's) during calibration runs however, and was observed to function well.

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LIST OF SYMBOLS

Symbol	Definition
A	Area, ft^2
a	Acceleration, ft/sec^2
a/g	Dimensionless acceleration
DC	Direct current
g	Acceleration of gravity, ft/sec^2
h	Height of water, inches
P	Pressure, lb_f/in^2
Q	Heat transfer rate, BTU/hr
Q/A	Heat flux, $BTU/hr\text{-}ft^2$
T	Temperature, degrees Fahrenheit
TC1, TC2, etc.	Thermocouple 1,2, etc.
$T_w - T_{sat}$	Difference between heater wall temperature and fluid saturation temperature at heater wall
V,v	Voltage, volts
γ	Specific weight, lb_f/ft^3

Subscripts

sat	Saturation
w	Wall

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SECTION I

INTRODUCTION

1.1 Background.

In recent years, the phenomenon of boiling has been extensively studied. The effects of various parameters upon the boiling process are of interest. Tong [1] itemizes these parameters and discusses each to some extent. The effects of acceleration are considered in this report.

The pool boiling process is normally depicted on a plot of log(Q/A) versus log $(T_w - T_{sat})$, which is shown in Fig. 1. Natural convection (Regime 1) occurs at the lowest heat fluxes and temperature differences $(T_w - T_{sat})$. Nucleate boiling (Regime 2) is characterized by the appearance of bubbles. The motion of these bubbles agitates the fluid and brings about an increased ability to transfer heat. The nucleate boiling regime is separated from the transition regime by the burnout point, also called the boiling crisis and the departure from nucleate boiling. The transition regime (Regime 3) is unstable and is characterized by a rapid loss of heat transfer capability. Boiling in the stable film regime (Regime 4) produces, as its name implies, a film jacket about the heater surface. An increase in surface temperature in this region brings about an increase in heat transfer capability with radiation transfer playing an increased role.

1.2 Previous Studies

Acceleration effects on pool boiling have been investigated but the amount of information to date is not extensive.

Merte and Clark [2] utilized a pivoted test vessel on a centrifuge that underwent rotational accelerations from 1 to 21 times normal gravity. The heat flux was varied from 5,000 to 100,000 BTU/hr-ft^2 and the fluid

used was distilled water. Pivoting of the test vessel maintained the acceleration normal to the boiler surface. They reported that an increase in acceleration brought about an increase in $T_w - T_{sat}$ at the higher heat fluxes and a decrease in $T_w - T_{sat}$ at the lower heat fluxes. This reversal in trend occurred near 50,000 BTU/hr-ft^2.

Beckman and Merte [3] conducted a photographic study of pool boiling undergoing acceleration. A centrifuge was used to produce the accelerations, which were varied from 1 to 100 times normal gravity. Heat fluxes from 16,000 to 72,000 BTU/hr-ft^2 were used. Bubble growth rates, departure diameters, and frequency data were included.

Costello and Tuthill [4] conducted research at higher acceleration levels and heat fluxes than Merte and Clark. Their apparatus consisted of a rotating pyrex pipe with a chromel C heater strip on the inside surface. Acceleration levels studied were 1 and 20 to 45 g's. Heat fluxes were varied from 100,000 to 200,000 BTU/hr-ft^2. Water was the working fluid. Higher superheats were found to be required in order to maintain a given heat flux as a/g was increased from 1.

Graham and Hendricks [5] conducted experiments up to 9 g's. They determined that an increase in a/g of the system delayed the transition from nonboiling to boiling.

Adelberg [6] provided a thorough review of the literature available in 1967. He discussed the effects of gravity on heat transfer relationships.

Adelberg and Schwartz [7] mounted a boiler on an 18 foot radius centrifuge to examine the effects of acceleration. The range of accelerations attained, in addition to 1 g, was from 20 to 134 g's. Photographic data were obtained through the use of a camera mounted at the center of the centrifuge. The heat flux range was varied from 9,500 to 150,000 BTU/hr-ft^2.

Based upon their own experimental data and data of previous investigators they concluded that, depending upon the interpretation of the data, gravity had either a direct effect on nucleate boiling or it had only an indirect effect brought about by the local variation in hydrostatic head.

The most recent and comprehensive research to date was done by Gray, Marto, and Joslyn [8]. The performance of a rotating boiler undergoing accelerations up to 475 g's was evaluated. Heat transfer coefficients were obtained up to 200 g's. The heat fluxes used were from 12,400 to 505,000 BTU/hr-ft^2. Photographic data were obtained as well. The effects of acceleration on the boiling curve as postulated in their report are shown in Fig. 2. At present, there is no theory available to prove their postulation and there is not enough experimental data to completely verify it.

The primary objective of this report was to extend a/g to 1800 in an effort to obtain more experimental data. Secondarily, the centrifuge assembly was constructed to provide a high-G facility for use in future burnout studies, heat pipe experiments, etc.

SECTION II

APPARATUS

2.1 Centrifuge

The centrifuge facility designed and constructed by Anderson [9] was used to produce the required accelerations. A detailed description of this facility may be obtained in reference [9]. Briefly, the facility consists of a control room and a protected blast-proof cell in which the centrifuge itself is located. The centrifuge is powered by a Chevrolet engine with an automatic transmission. Operation is exercised remotely from the control room. Photographs of the system are given in Figs. 3, 4, and 5. Figures 6 and 7 schematically show the system.

A new centrifuge arm was designed for this project. It was designed to operate at speeds up to 1450 RPM and was of essentially symmetrical construction. Both the counterweight and the boiler cradle assembly were hinged. Each side had an identical condenser, the one on the counterweight side a dummy. This was to ensure that the drag force being created was equal on both sides. The arm was manufactured from high quality 2024 T 351 aluminum as were all load carrying components. Bolts and pins were of high strength steel. A detailed stress analysis was conducted. The calculations showed that no portion would be loaded beyond six-tenths yield at maximum RPM.

2.2 Boiler-Condenser Assembly.

The boiler was constructed from a 2¼ inch outside diameter aluminum tube. Four viewports were cut into the sides. The two inboard ports allowed viewing the liquid level. The two outboard ports were intended to provide a view of the boiler surface and the boiling process. The boiler may be seen in Figs. 8 and 9.

A copper block 2-3/4 inches long and 1½ inches in diameter formed the

boiler block (See Fig. 9). Nine feet of Amperex Thermocoax 1NcI15 heater wire was wound at the far outboard end and silver soldered into place. The .020 inch nichrome wire that formed the heater element was silver soldered to a short copper lead. The entire base of the boiler block was then coated with Astroceram ceramic cement and baked. This prevented working of the nichrome wire and was intended to keep it from grounding. The surface of the boiler block where boiling occurred was polished to a mirror finish. See the Experimental Procedures section for a description of the polishing process.

The entire boiler assembly was cradled and hinged to maintain a level head of water in the boiler. Physical constraints on the system allowed depression to an angle of 12 degrees from the horizontal only. This fixed the minimum acceleration force level that could be produced and still maintain a level surface of fluid. This minimum acceleration was 5 g's, the corresponding minimum RPM was 72. However, this was well below the lowest stable RPM of the system. The minimum stable RPM was found to fluctuate from day to day but was approximately 200-220 RPM (37-45 g's).

Steam being produced in the boiler flowed to the condenser radially inward through a flexible connecting tube at the top of the boiler. The steam was condensed and was then returned via the same path to the boiler. The entire process was maintained at atmospheric pressure by a vent at the far inboard end of the condenser. The condenser was a straight tube externally finned and subjected to air flow produced by the rotation of the centrifuge arm. Access ports were machined into the arms in order to provide for sufficient air flow (See Figs. 5 and 10).

2.3 Power Circuitry.

The power supply for the electrical resistance heater wire consisted of a 208 volt supply which was fed into a General Electric Form HK induction regulator that could raise or lower the input voltage by 100%. The output of the regulator then formed the input to the power slip ring assembly. It was monitored on a Westinghouse Type TA Industrial Analyzer in the control room. The power slip ring assembly consisted of a pair of copper slip rings each fed by two carbon brushes (See Fig. 11).

2.4 Information and Control Circuitry.

RPM count was obtained through the use of a SPACO type PA-1 magnetic pickup. The slotted timing gear for the pickup was located on the drive shaft near the base of the centrifuge. The output was displayed as RPM/2 on a Berkeley Model 5545 EPUT Meter (See Figs. 3 and 7).

Excessive vibration of the system was detected by a Stratham accelerometer (+8 g's to -3 g's) mounted on the upper housing of the centrifuge. Power for this system was supplied by a Transistorized Power Supply Model 2015R. The output of the accelerometer was passed through a COHU Amplifier Model 112A. It was then monitored on a Heathkit Oscilloscope and was also displayed on warning lights (See Figs. 3, 5 and 7).

A bomb-proof, remote TV camera was used in conjunction with a General Radio Company type 631-B Strobotac to provide video coverage of the centrifuge in operation. A Diamond ST2 Videcon camera was mounted looking vertically downward through the viewport in the boiler. The strobe light performed two functions: it provided illumination upward through the viewports, and it "stopped" the arm so that it could be viewed on the Setchell Carson model 2100SD monitor. The frequency of the strobe light was controlled remotely by synchro transmitter-receivers (BUORD MK 8 MOD4A). The

resulting image on the screen was magnified several times (See Fig. 7).

A pressure transducer, CEC type 4-312 150 psi, was mounted at the base of the boiler. The pressure face of the transducer was exactly parallel to the boiler's polished surface and was located at the same radius (See Fig. 9). Power for its operation was supplied by an Eveready nine volt transistor battery located near the center of the centrifuge. Both the power lead to and the information lead from the transducer were shielded. The millivolt output of the transducer was fed directly into a special DC amplifier (See below). Calibration of the pressure transducer is described in Appendix A.

The thermocouples were Minneapolis-Honeywell copper constantan B&S gage 24 with fiberglass insulation. Four were located in the boiler block as shown in Fig. 11. One was located in the vapor space above the fluid in the boiler. The thermocouples were led from the boiler assembly at the extremity of the arm to the special DC amplifiers and reference junction. These were located near the center of the centrifuge arm. The reference junction was maintained at 32 degrees Fahrenheit by a small plastic bottle ice bath. A wiring diagram is shown in Fig. 12 and the locations of the thermocouples are shown in Fig. 13. Calibration of the thermocouples is described in Appendix B.

The DC amplifier package was designed to boost signals received from the thermocouples and the pressure transducer. There were six channels of amplification available, one for each of the five thermocouples and the remaining one for the pressure transducer. All input signals were in the millivolt range. The amplifiers' gain provided voltage outputs of from minus seven volts to plus seven volts. Each amplifier was built around the Fairchild UA709A operational amplifier. The power supply consisted of two RCA number 246 nine volt batteries located near the center of the arm.

A schematic of a single channel of amplification is shown in Fig. 14. The location of this unit is shown in Fig. 10.

Once amplified, the signals were sent to the Lebow Model 6109-12 instrumentation slip ring assembly. It had coin-silver slip rings and silver graphite brushes and was rated for operations up to 2000 RPM.

The readout equipment consisted of a six position selector board and a digital voltmeter. The voltmeter was a four place Systron Model 1230. Both items were located at control station number two (See Fig. 4).

SECTION III

EXPERIMENTAL PROCEDURES

3.1 Preparation of Boiler Surface.

In order to ensure that boiling action occurred at the center of the boiling surface, four small artificial cavities were drilled near the center. These were .015 inches in diameter and several diameters deep. They were arranged in a non-symmetric pattern.

The boiler surface as delivered after machining was in excellent condition and required hand sanding on grade 0 emery paper only. It was sanded maintaining the line of action and then rotated 90° and sanded again.

Four Buehler metallurgical polishing wheels were used to complete the process. The first was a canvas covered wheel and used 600 grit carborundum in water as abrasive. The second was felt covered with alumina in water as abrasive. The third was kitten ear covered with gamma-alumina in water as abrasive. The final wheel was velvet impregnated with three micron diamond dust. Methanol was used to wet this surface. On each wheel, the surface was polished, raised, rotated 90°, and polished again. The surface was then thoroughly cleaned with methanol and dried under a hot air blower.

Finally, the artificial cavities were cleaned out using the original drill. The surface was inspected for scratches.

3.2 Boiler Assembly and Mounting.

The boiler was assembled by inserting the boiler block into the boiler from the bottom. The seal, a ring cut from a piece of 1/8 inch Viton, was put into place around the boiler block. The steel securing ring was then threaded onto the base of the boiler until the thermocouple holes lined up. This step required the use of a vise in order

to thread the ring all the way on and in order to have the seal properly seated (See Fig. 9).

The boiler was then ready to be mounted on the centrifuge. The thermocouples were inserted into the wells. A piece of strip asbestos was wrapped over them and around the base of the boiler. The asbestos was held in place with a securing wire. The pressure transducer jack was attached and the boiler was then put into the cradle on the centrifuge. The power leads and the bottom of the boiler block extended through the hole in the cradle assembly. The power leads were then attached and the boiler screwed down. The flexible tubing was put onto the top of the boiler at the same time the boiler was sliding into place on the cradle assembly. The flexible tubing was secured with a clamp to the top of the boiler and the backing plate was bolted down.

Final preparation required removing the upper inboard viewport and filling with 125 cc's of distilled water. The viewport was then secured and the entire assembly checked for leaks.

3.3 Fluid Preparation.

Distilled water was used for all calibration runs. No special precautions were taken to ensure degassing of the fluid. The water was not preheated prior to any runs.

3.4 Proposed Testing Procedure.

Once the calibration of the pressure transducer is complete, the heat losses from the boiler have to be estimated. This procedure would be done by filling the boiler with asbestos or fiberglass, applying voltage to the heater wire, and measuring the heat flux through the boiler block. The centrifuge would be run at different RPM while this test is in progress. A heat flux versus RPM plot would be made and used to estimate the heat losses.

The centrifuge would then be ready for collecting data. A proposed testing procedure would be as follows:

1. Set the engine control at some nominal value and allow it to settle on an RPM.
2. Set the induction regulator for some predetermined nominal heat flux and allow the system to come to equilibrium.
3. Take a round of readings; i.e., TC1-TC5 and the pressure transducer output.
4. Repeat the procedure at different RPM settings, but at the same heat flux.
5. Change the heat flux to a new nominal setting and repeat steps one and three.

SECTION IV

RESULTS

No boiling results were obtained due to numerous equipment difficulties which proved to be time consuming.

One of the first problems was the heating up of the upper and lower bearings on the centrifuge. This occurred during the initial turnup. The arm was removed and checked for proper balance. There was no imbalance. The upper bearing was removed with no discrepancy noted. The centrifuge was reassembled and run. No further bearing heating occurred.

The second problem was encountered in the information slip ring assembly. During some preliminary checks on the thermocouples, it appeared that the output of the amplifiers was non-linear. Further checking, however, revealed that a partial breakdown of insulation existed between several of the slip rings. This necessitated removal of the arm assembly and a thorough cleaning of the slip rings. The upper two channels could not be properly cleaned and remain unusable. There were still sufficient channels available to pass the desired information.

The original seal in the boiler was a Parker Viton "O" ring. This performed satisfactorily at low RPM but did leak at higher acceleration levels. It was replaced with a rectangular cross section ring cut from a sheet of 1/8 inch Viton. No further leakage problems were encountered.

The 4½ volt batteries originally intended for use in powering the DC amplifiers proved to be inadequate. These were replaced first by RCA number 246 nine volt batteries and then by Eveready nine volt Energizers. These were both found to operate satisfactorily as long as the batteries were fresh. The slightest deviation from nine volts, however, led to serious difficulties. The thermocouples were calibrated and curves were obtained using new batteries. Later, while correcting some minor problems

not connected with the amplifiers, a check on the calibration points was made. They displayed a considerable shift. New batteries corrected the problem. The batteries removed registered very close to nine volts. From these observations it was concluded that the power supply must be regulated to maintain accurate readings. A suggested procedure is included in the Recommendation Section.

The method of keeping the heater wire from shorting to ground was not successful. Although no direct short occurred, the initial several megohms to ground gradually deteriorated to a few thousand ohms. The noise produced caused fluctuations in the digital voltmeter. Attempts to correct this problem proved futile since the wire had been silver soldered in place. Suggestions for improvement of the heater are included in the Recommendation Section.

The TV video system provided an image but was not entirely satisfactory. The main problem was the difficulty in stopping the centrifuge arm directly under the camera. A suggested improvement is included in the Recommendation Section.

SECTION V

RECOMMENDATIONS

The following recommendations are made concerning equipment modifications:

1. Streamline the centrifuge arm assembly to decrease drag and increase the maximum RPM attainable.

2. Change the flexible tubing between the boiler and the condenser to one more easily removed. It is felt that two pieces of aluminum tube would be satisfactory, one sliding inside the other. Acceleration levels requiring the angling of the boiler are below the minimum stable RPM of the system so the coupling need not bend.

3. Increase the size of the ice bath reference to provide for longer runs. It was found that runs of longer than one half hour's duration required additional ice.

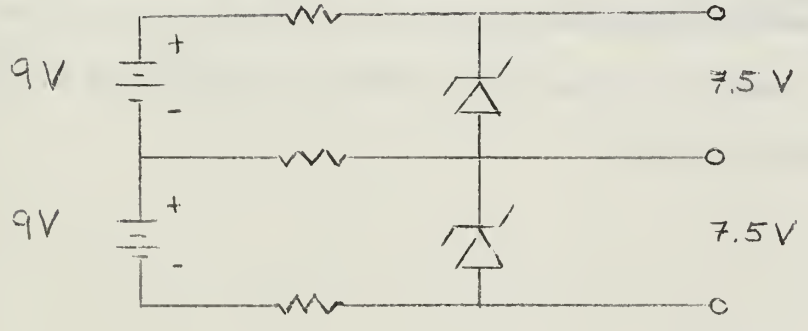
4. Change the boiler block from copper to some material less easily corroded, possibly nickel.

5. Use Thermo Electric Ceramo 1/25 inch thermocouple wire in place of that described in Apparatus. An ungrounded junction is recommended so that any noise that might be produced by the heater would not affect the thermocouples. Use of a stiff wire such as this would facilitate insertion into the thermocouple wells. An alternative is to redesign the boiler to provide for permanent installation of the thermocouples.

6. Improve the heater wire arrangement. The idea of winding and soldering the wire at the base of the boiler block should be retained. However, a minimum of silver solder should be used in case removal becomes necessary. Also, the first and last several turns should be left wound but not soldered in place. This is to provide for sufficient lead

should it be needed. The .020 inch nichrome wire should be soldered to a plug-in or screw-in type connecter. The entire assembly should be held in place by several coatings of Astroceram. The only visible portion when completed should be the connecter. This would considerably facilitate handling. The region between the connecter and the nichrome wire is critical in that this is where grounding is most likely to and did occur.

7. Provide for a regulated power supply. Using a standard DC power supply is a possibility. The current required would have to be carefully checked, however, since the Lebow slip rings are rated at .2 amperes only. In addition, continuous current through these slip rings is not recommended. A regulator for the present batteries should be satisfactory. Two zener diodes operating at a cutoff of 7.5 volts is a possibility. The voltage level of 7.5 is not critical but zener diodes of this type are known to be available. A suggested schematic is shown below.



Although it is not known to be a problem, it is recommended that the pressure transducer be provided with a regulated power supply also. Use of the same one as above should be investigated.

8. Provide a means of triggering the strobe with the output of the SPACO magnetic pickup. Such a system would facilitate the procedure for "stopping" the arm.

9. Move the pressure transducer away from the side of the boiler in order to minimize the heat effects. Most of the heat reaching the transducer is suspected to be conducted via the aluminum support which is attached to the boiler. Separating the transducer from the boiler and moving it might prove feasible. The difficulty here is that space is at a premium and that the face of the transducer should be at the same radius as the boiling surface.

The following recommendations are made concerning future experiments:

1. Complete the above equipment changes and operate the system to extend the a/g effect data on pool boiling to the maximum capacity of the system.

2. Obtain pictures of the boiling process under acceleration by: (a) utilizing the outboard viewports and the TV strobe system, or (b) using a system of mirrors and a high speed camera; the image can be passed from the boiler to the centerline of the arm and then vertically upward and photographed.

3. Extend the study to the effect of gravity on the nucleate boiling critical heat flux.

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APPENDIX A

PRESSURE TRANSDUCER CALIBRATION

During a preliminary calibration run, it was noted that the pressure transducer was sensitive to the heat flux in the boiler. It was therefore necessary to calibrate the transducer taking this effect into account.

The boiler was first filled to a known height of water (2-5/8 inches) with a known amount of water (125 cc's). Knowing the RPM of the system, and thus the acceleration on the column of water, the pressure acting on the face of the transducer could be calculated. A table of values of pressure versus RPM was compiled.

A known temperature was then produced at the thermocouple nearest to the boiler surface. Thermocouple number three was chosen because number four was, at that time, inoperative. The centrifuge was then operated from the minimum stable RPM, 200-220 RPM or 37-45 g's, to 460 RPM or 204 g's while maintaining the temperature at number three. The temperature was held constant by varying the voltage input through the induction regulator. Runs were made at temperatures of 74, 126, 153 and 180°F. These results are shown in Fig. 15 as a plot of pressure transducer output versus RPM/2 for a given temperature. Values were taken from this plot and used to construct Fig. 16, which is a plot of transducer output versus temperature for a given RPM/2.

The original intention was to conduct further runs at temperatures of at least 210 and 230°F. These would be used to extend both plots described above. Figure 16 was to be extrapolated. Values would then be taken from the extrapolated plot and used to construct a figure similar to Fig. 15. The difference would be the abscissa, which would be pressure

in psia. The pressure would then be calculated from the hydrostatic head relationship corrected for acceleration,

$$P = (a/g)\,\gamma\, h$$

Pressure transducer calibration was not concluded due to the breakdown in the ohmage to ground of the heater wire and the accompanying noise problem.

The error in the calculation of pressure by this method may be estimated as follows:

P_{atm} = Atmospheric pressure

P_a = Pressure due to acceleration

γ = Specific weight of water, 60.1 lb_f/ft^3 at 200°F.

h = Height of water, 2-5/8".

RAD = Radius to cg of column of water, 33-17/32".

$\Delta RPM = 2$ rpm

$\Delta RAD = 1/16"$

$\Delta h = 1/32"$

$\Delta \gamma = .5\ lb_f/ft^3$

$200 \leq RPM \leq 460$

$$P = P_{atm} + P_a$$

$$P_a = (a/g)\,\gamma\, h$$

$$(a/g) = \left(\frac{RPM}{g}\right)\left(\frac{2\pi \text{ radians}}{60 \text{ seconds}}\right)(RAD)$$

$$P_a = \left(\frac{RPM}{g}\right)\left(\frac{2\pi}{60}\right)(RAD)\,\gamma\, h$$

$$\frac{\Delta P_a}{P_a} = \frac{\Delta RPM}{RPM} + \frac{\Delta RAD}{RAD} + \frac{\Delta\gamma}{\gamma} + \frac{\Delta h}{h}$$

$$= \frac{2}{200} + \frac{1/16}{33\ 17/32} + \frac{.5}{60.1} + \frac{1/32}{2\ 5/8}$$

$$\frac{\Delta P_a}{P_a} = .032$$

The error in the calculated hydrostatic pressure is approximately three percent.

APPENDIX B

THERMOCOUPLE CALIBRATION

Calibration of the thermocouples was accomplished by using three known temperatures. These were an ice water bath (32°F), a steam jacket (211.2°F at 29.44 inches of mercury), and solidifying tin (449.44°F). A constant temperature ice water bath was also used for the reference junction. In order to keep the output of the thermocouples within the saturation limits of the amplifier, all were initially immersed in a bath of highly heated molten tin and the voltage output monitored. Adjustments were made as necessary to keep the voltage within $\pm$ 7 volts, the saturation limits.

Each thermocouple was immersed in first the ice water bath and then the steam jacket. Outputs as amplified and passed through the slip rings were monitored on the digital voltmeter. This provided the first two points on the calibration curve.

The third reference point for each was obtained by inserting the thermocouple in a small pyrex glass tube and immersing it in molten tin. The amplifier output was then monitored on two separate instruments, the digital voltmeter and a Hewlett Packard Moseley XY recorder. The abscissa for the XY recorder was the built-in variable, time. The ordinate was the amplifier output. A temperature versus time diagram was thus formed for solidifying tin. As the tin cooled, voltages were read from the digital voltmeter and marked on the XY recorder plot. The exact melting point manifested itself on the temperature-time plot by displaying a nearly constant voltage output for a period of time. Immediately prior and subsequent to the constant voltage portion, the temperature was observed to drop rapidly. The average of all points on the nearly constant

voltage line was taken and used as that corresponding to 449.44°F.

The results of the calibration process are tabulated below:

THERMOCOUPLE	ICE POINT Volts	BOILING POINT Volts	TIN MELTING POINT Volts
1	-0.468	+1.723	+4.571
2	-0.771	+1.408	+4.338
3	-3.673	-0.430	+3.698
4	-0.678	+1.629	+4.746
5	-2.684	+0.657	+4.999

A graph for each thermocouple was constructed and used to obtain the temperature for any given output voltage. All plots were linear (See Fig. 17).

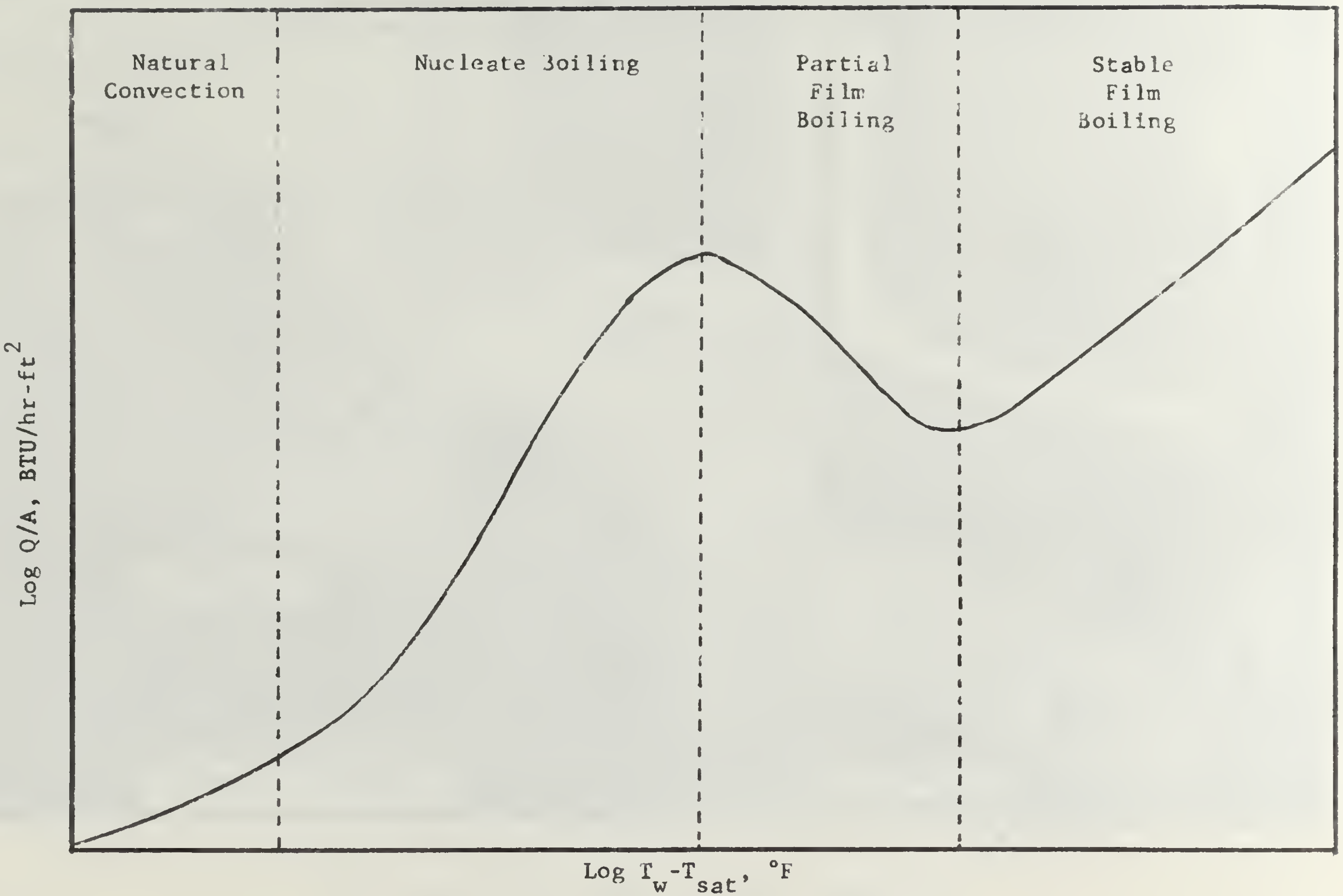

Fig. 1 Boiling Curve

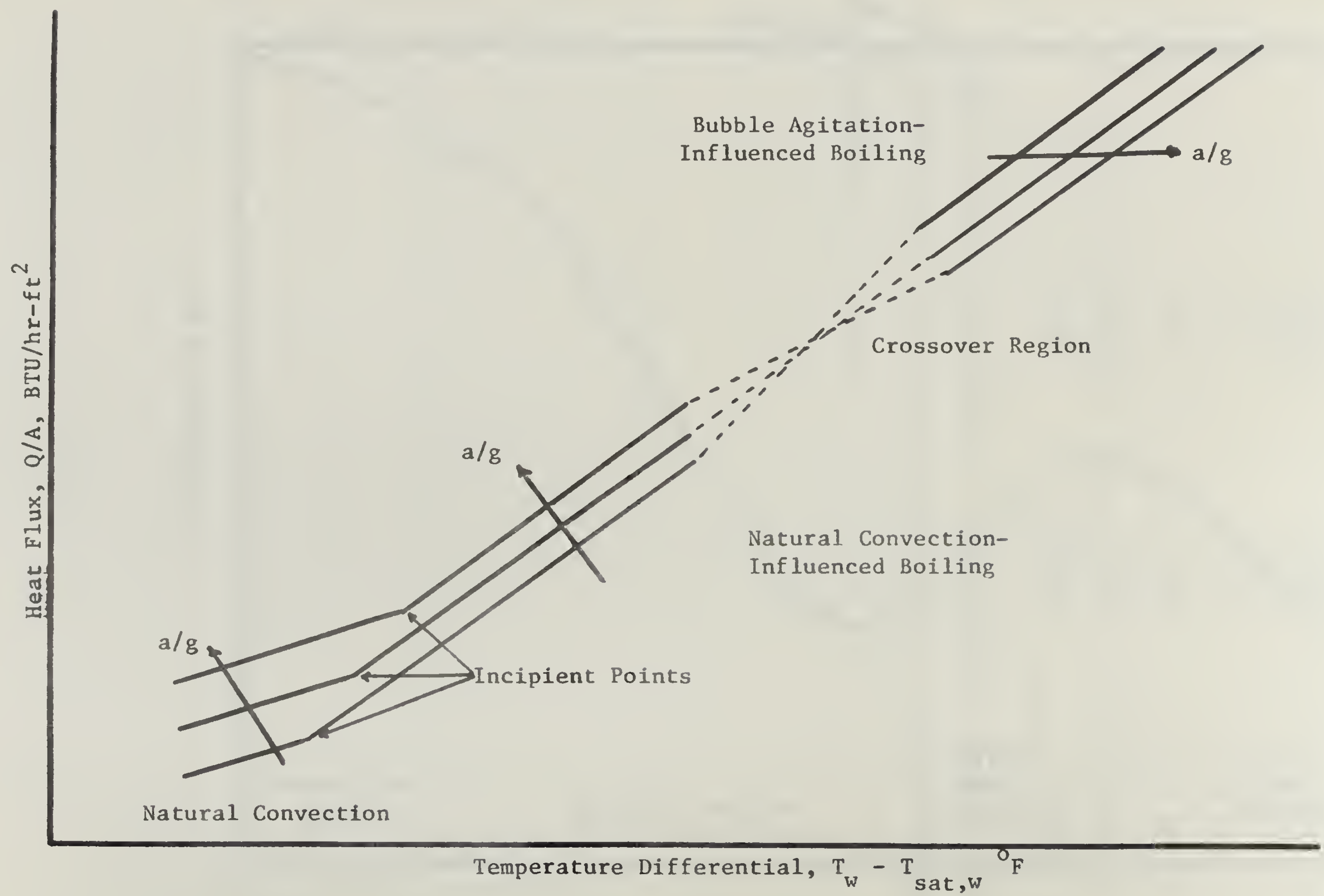

Fig. 2 Proposed Effects of Acceleration on Nucleate Boiling

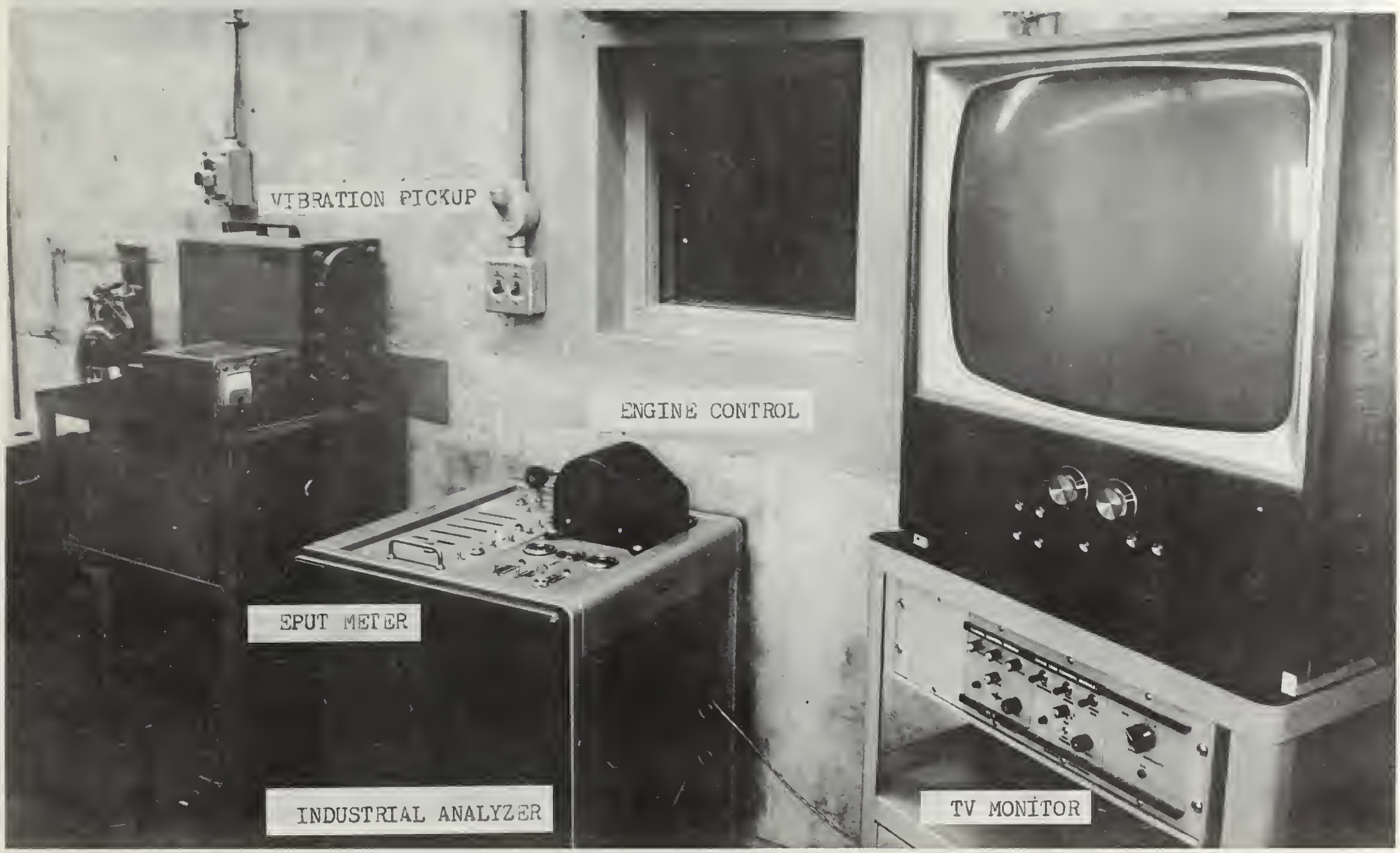

Fig. 3 Control Room, Control Station Number One

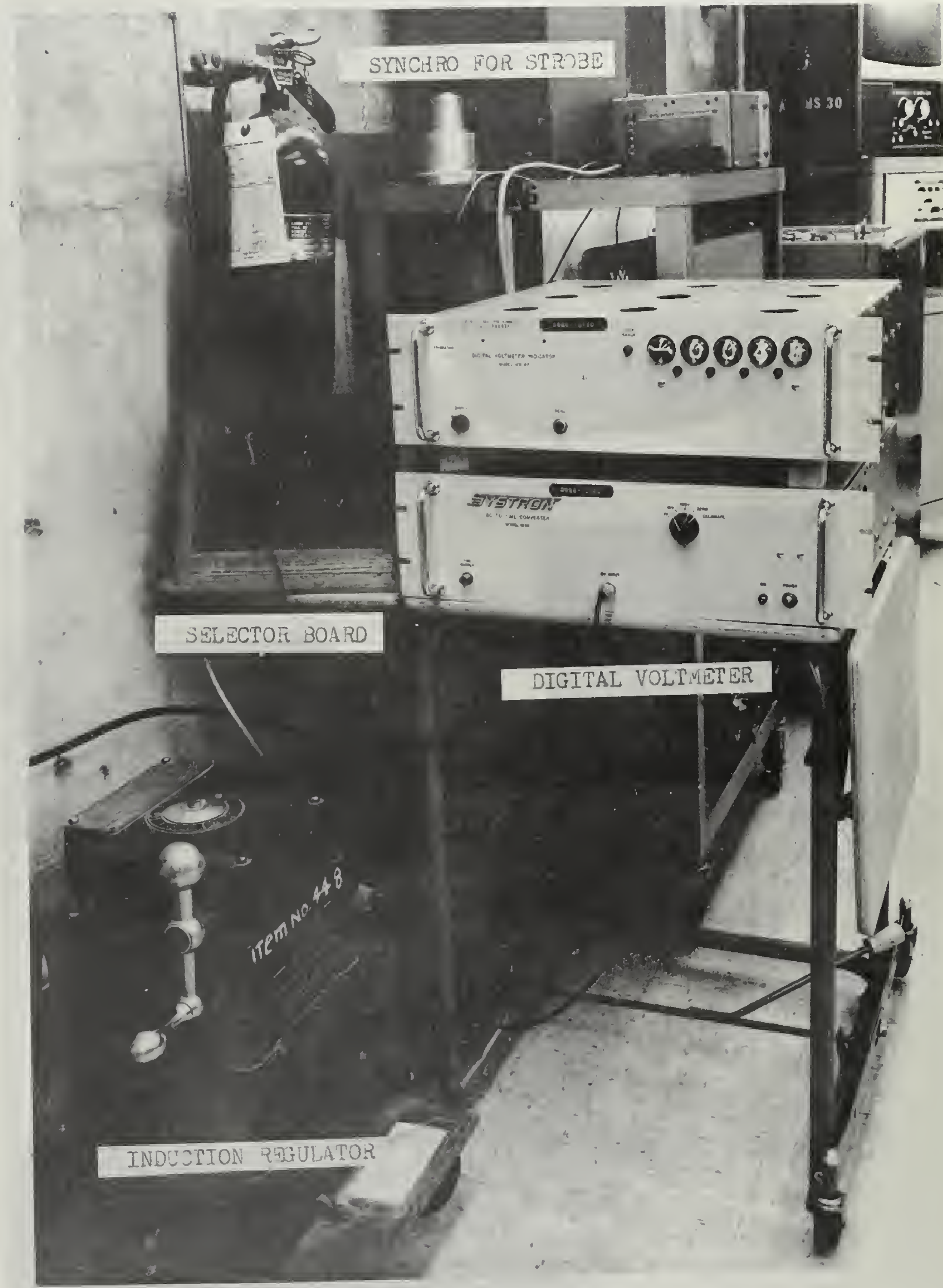

Fig. 4 Control Room, Control Station Number Two

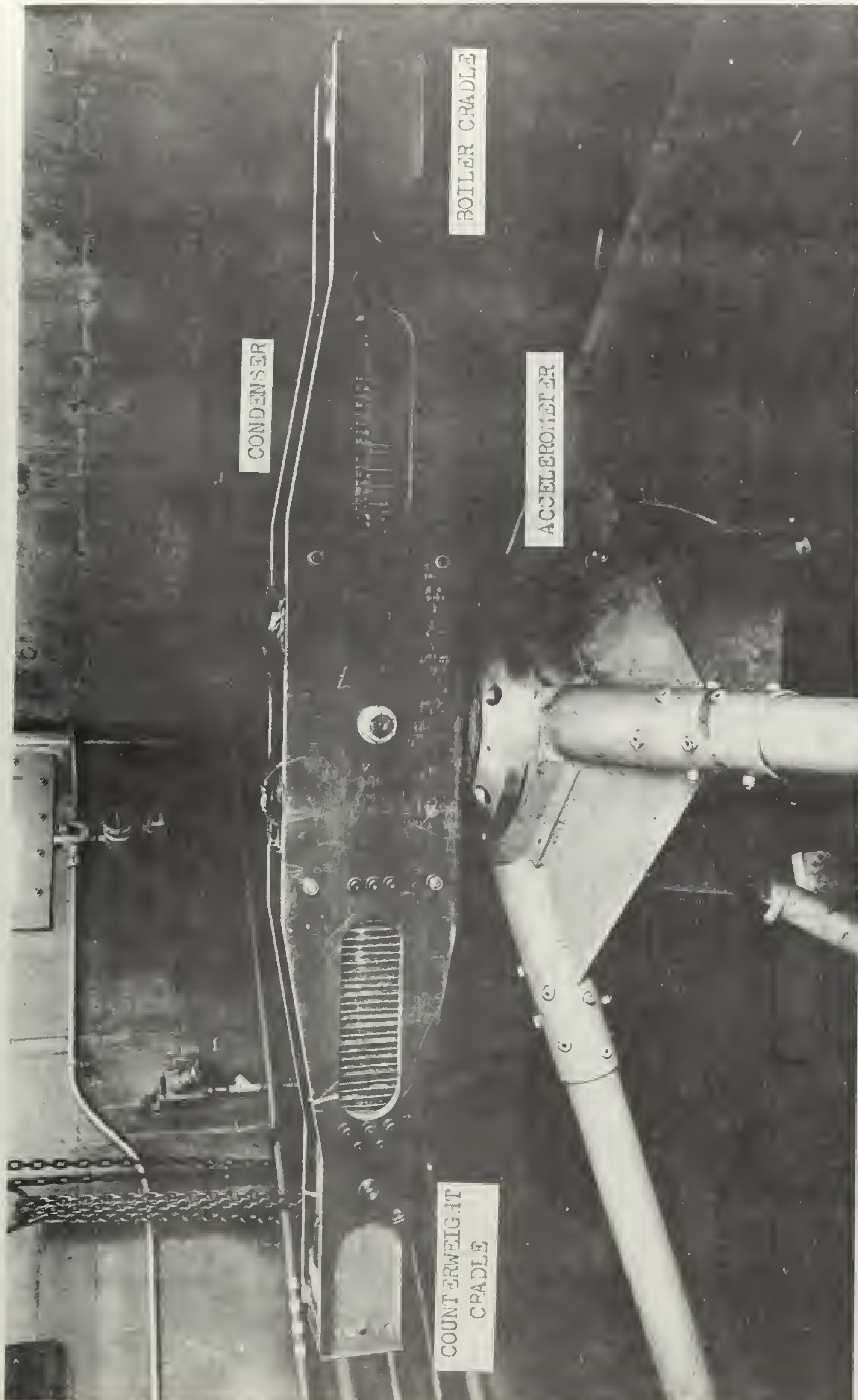

Fig. 5 Centrifuge

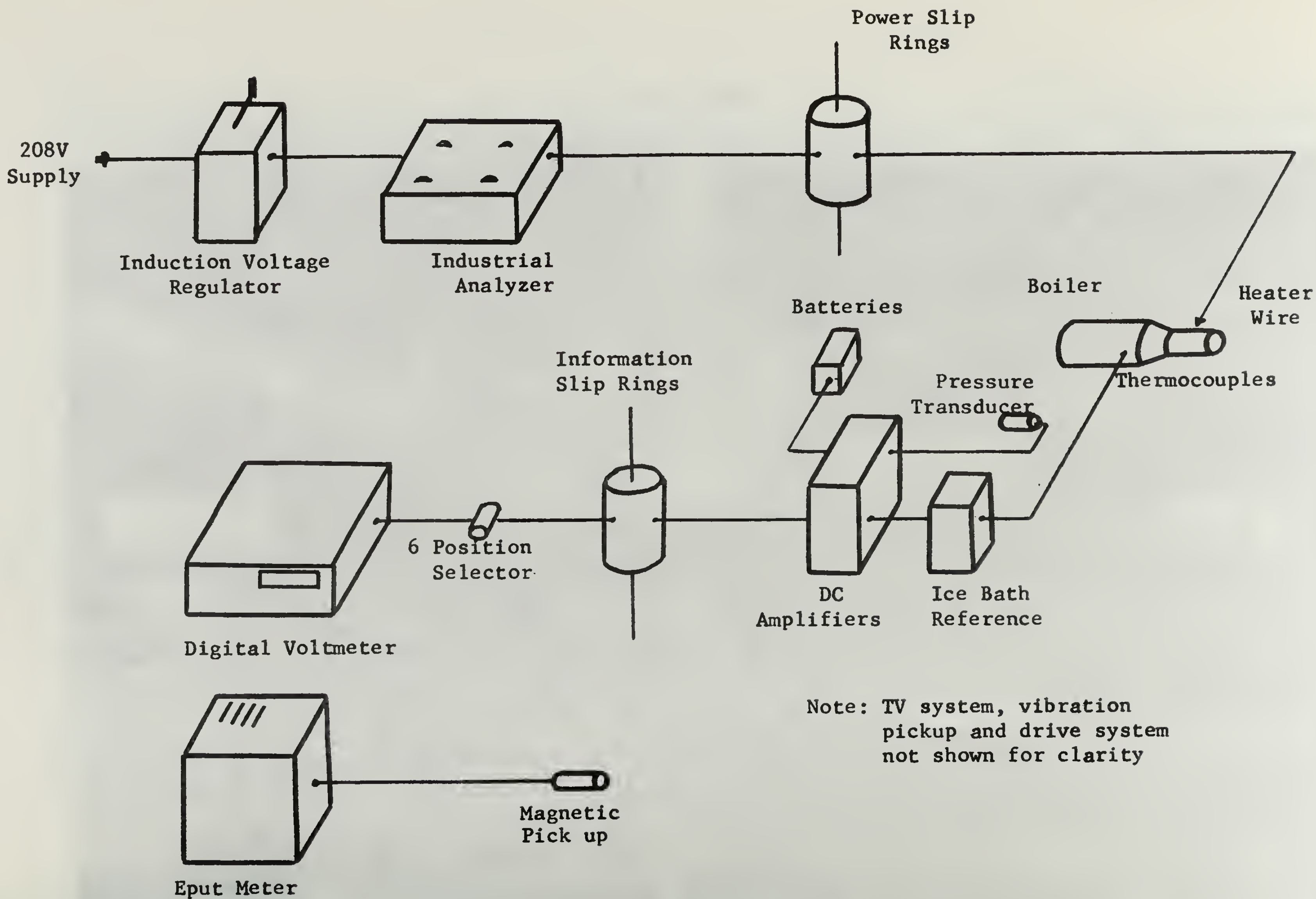

Fig.6 System Schematic

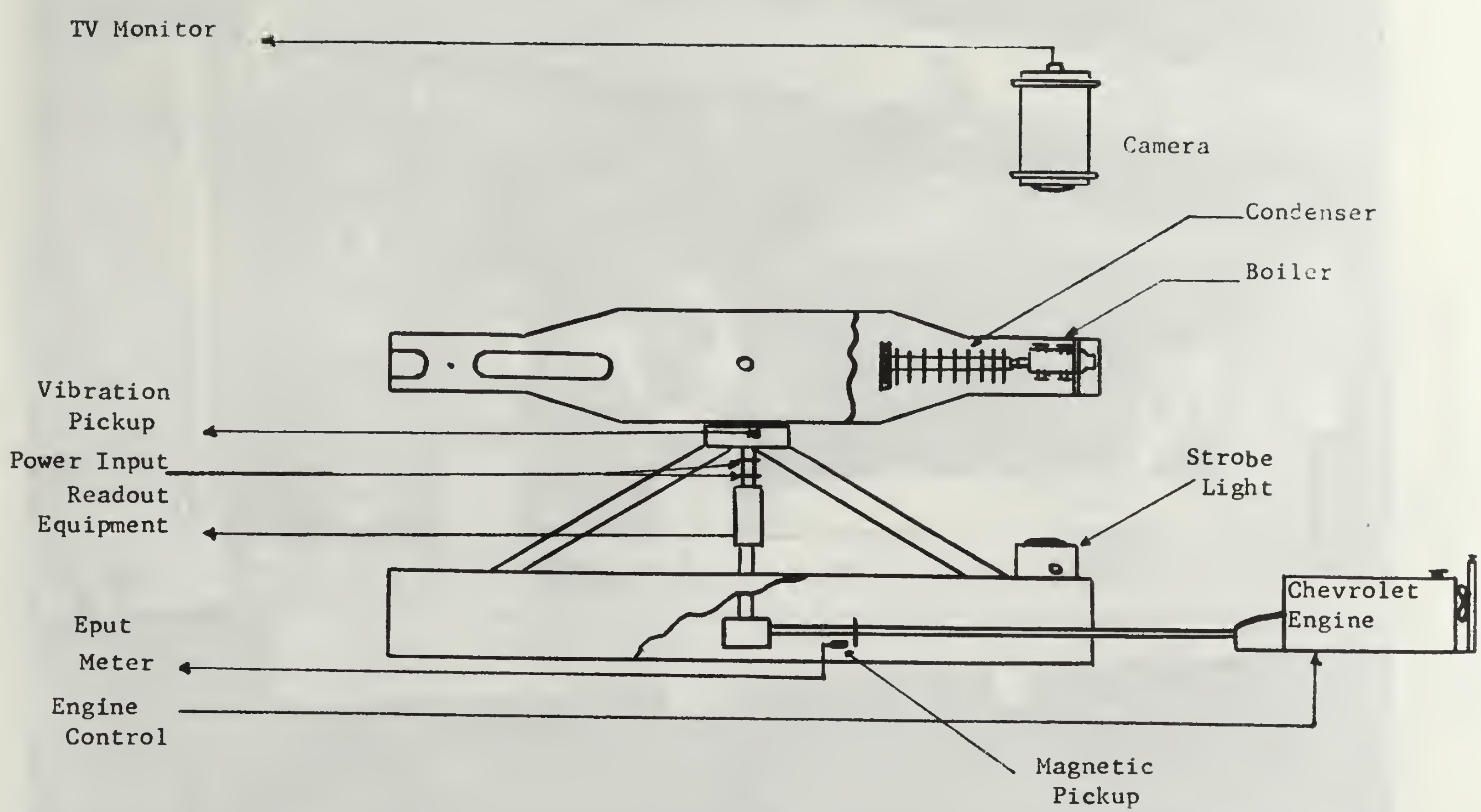

Fig.7 Centrifuge Schematic

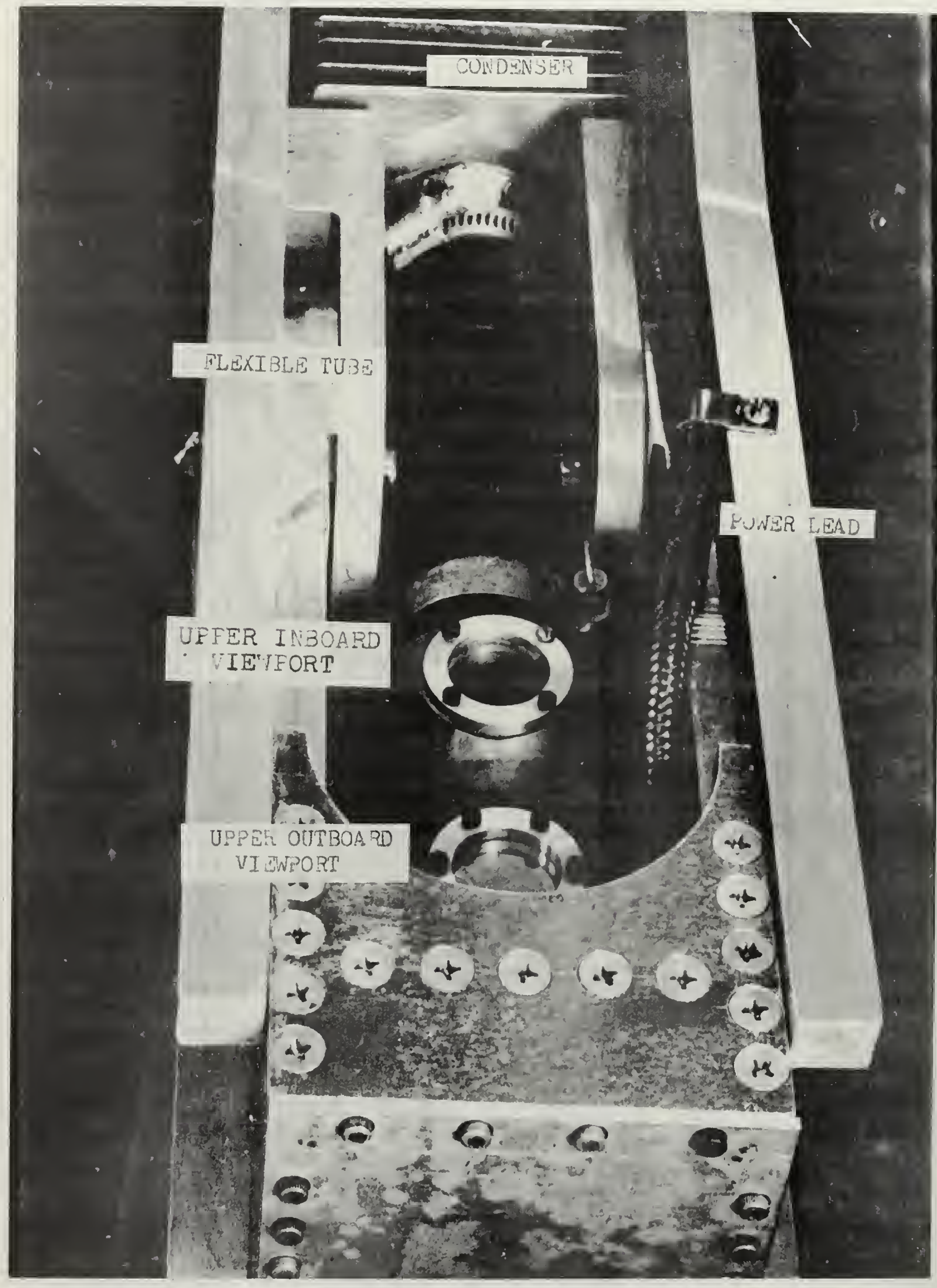

Fig. 8 Boiler Cradle

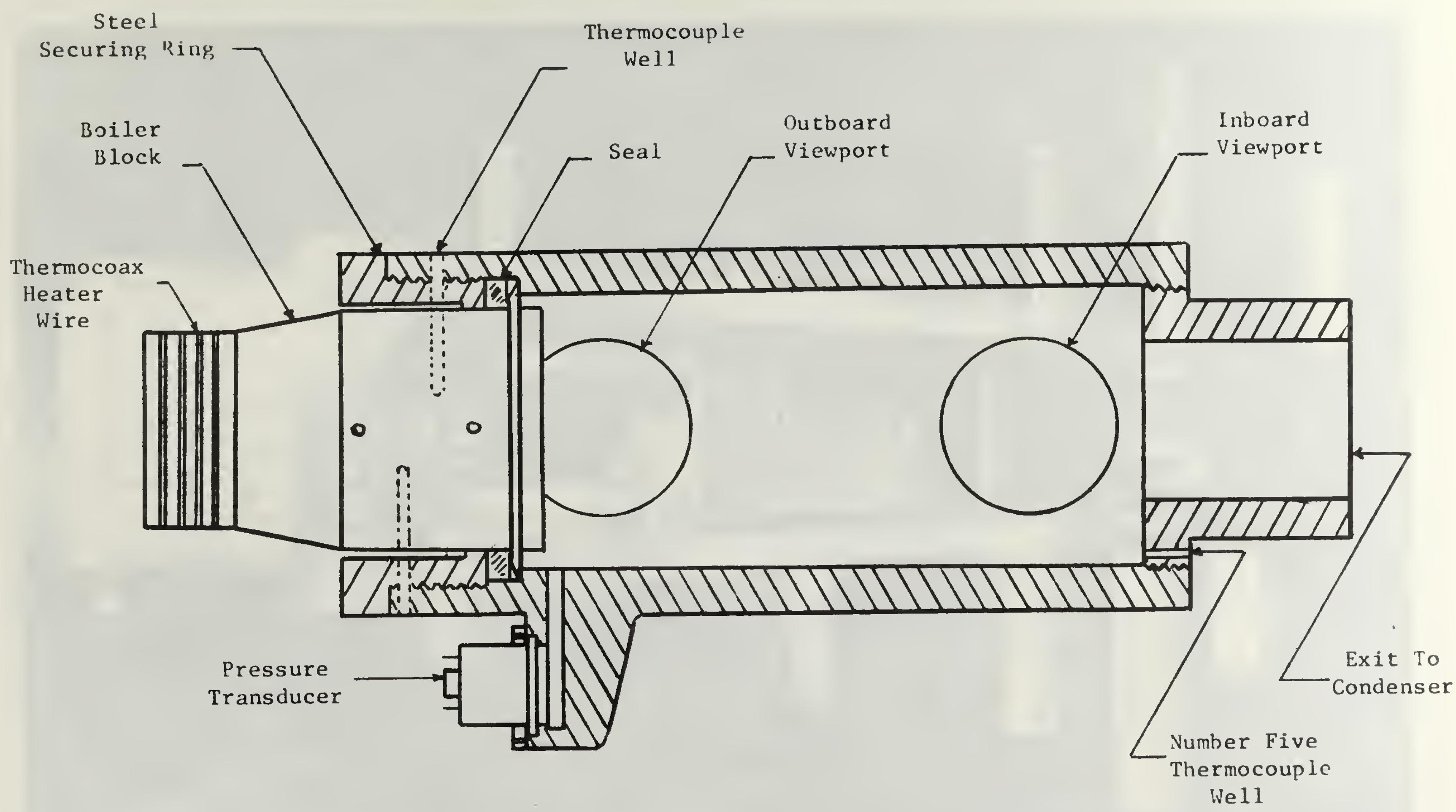

Fig. 9 Boiler Cross-Section

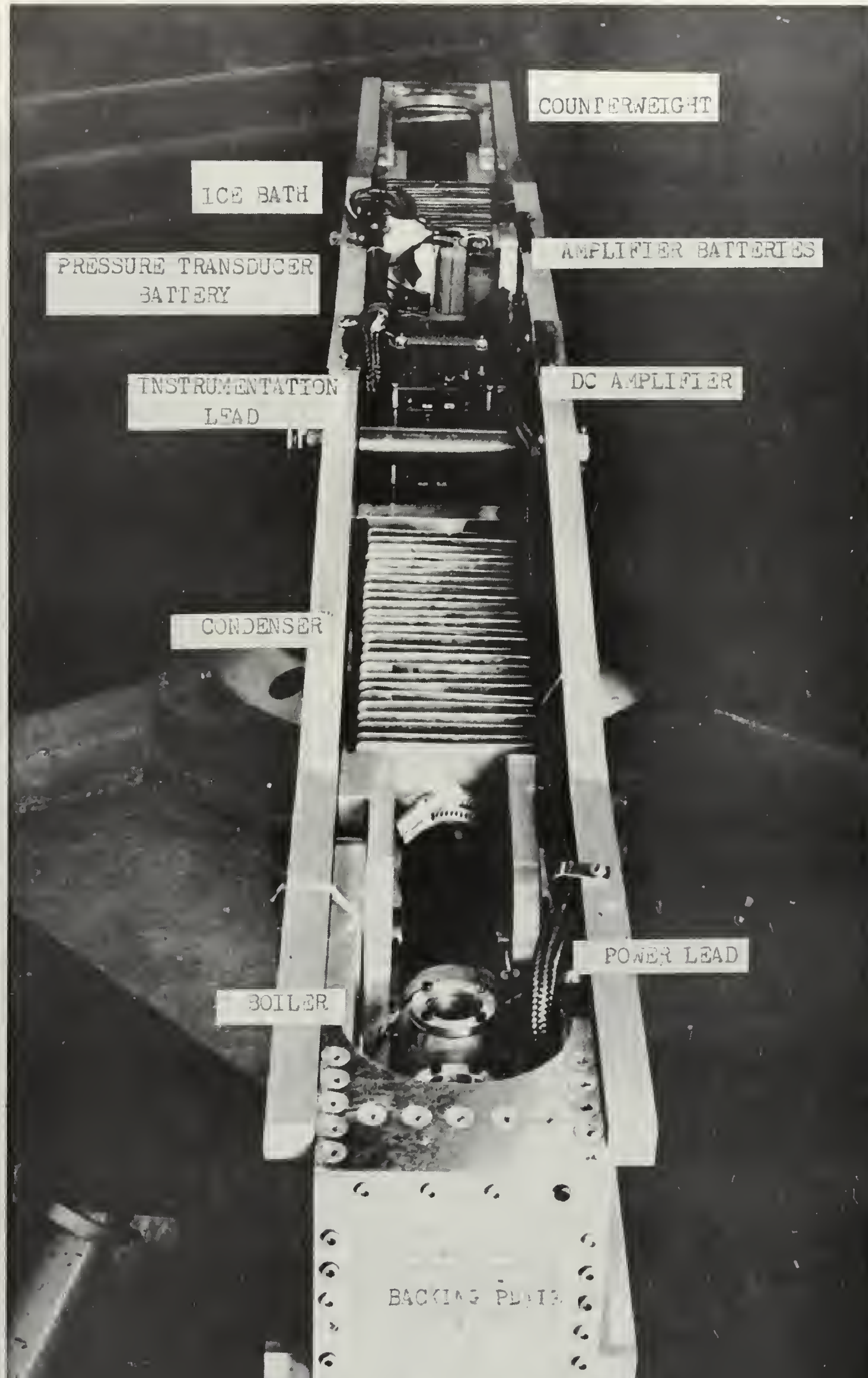

Fig. 10 Arm Assembly

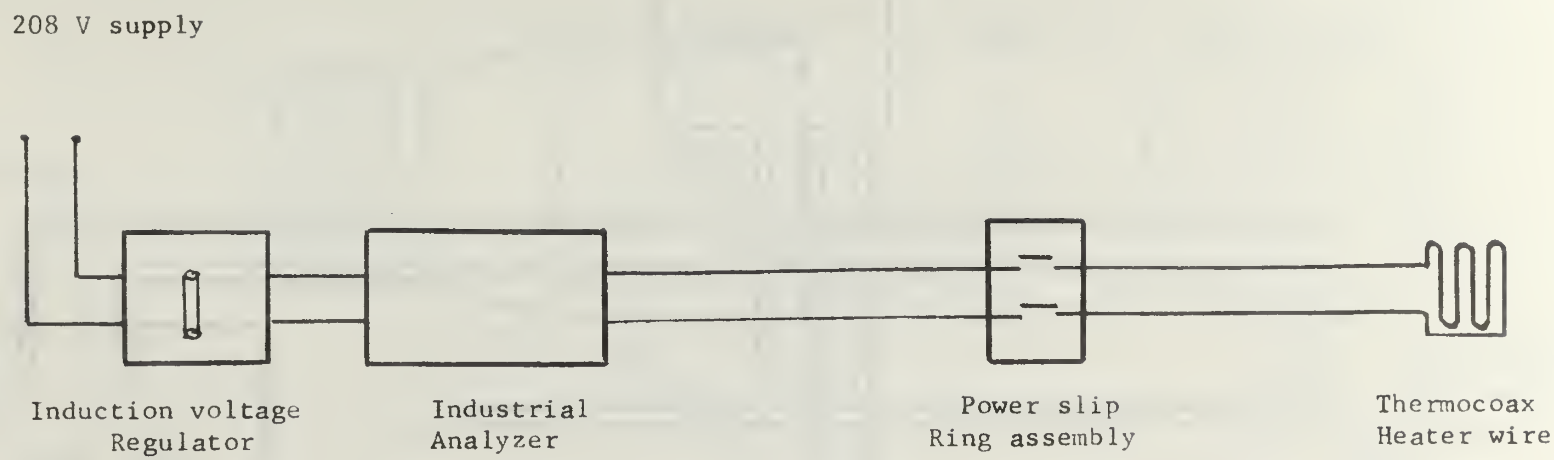

Fig. 11 Power Circuitry

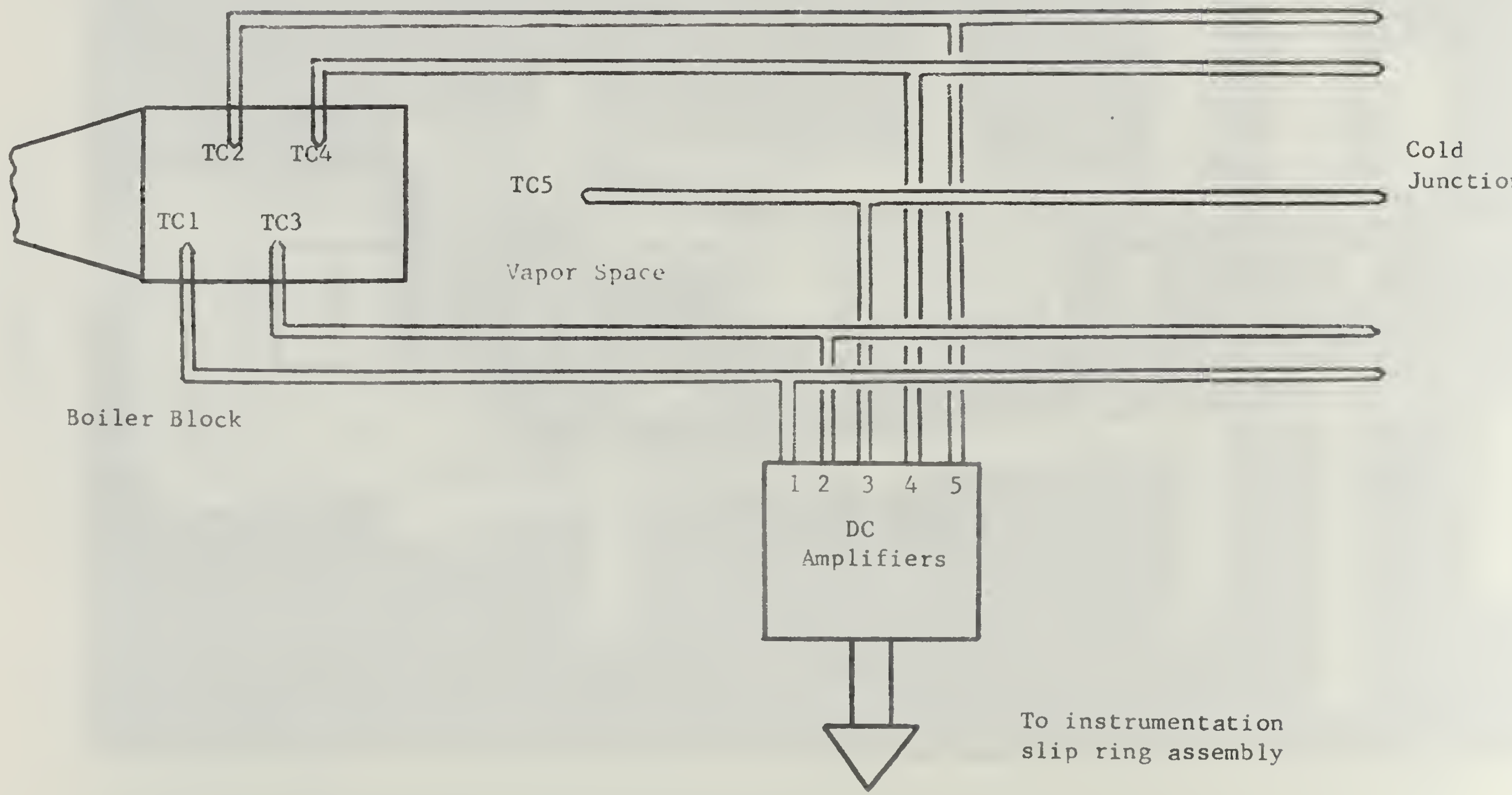

Fig. 12 Thermocouple Wiring

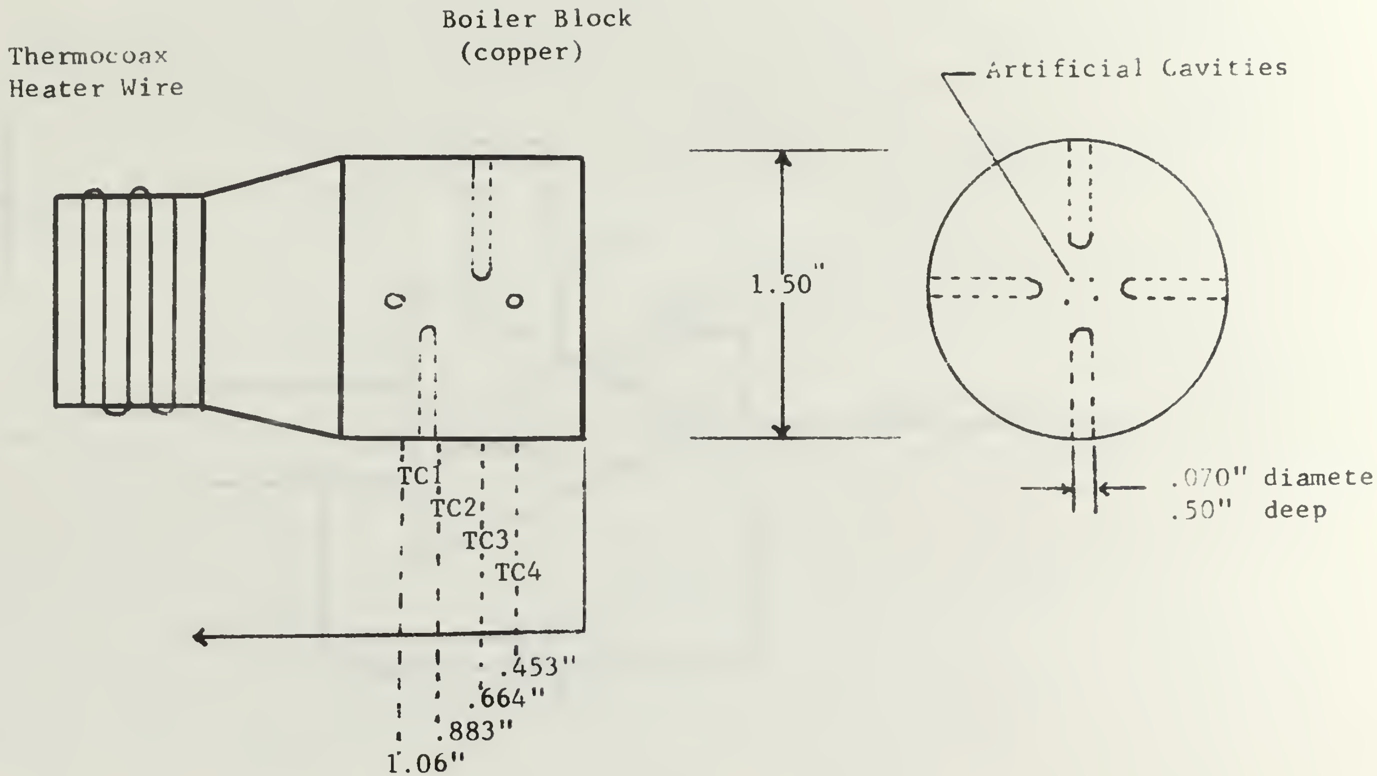

Fig. 13 Location of Thermocouples TC1-TC4

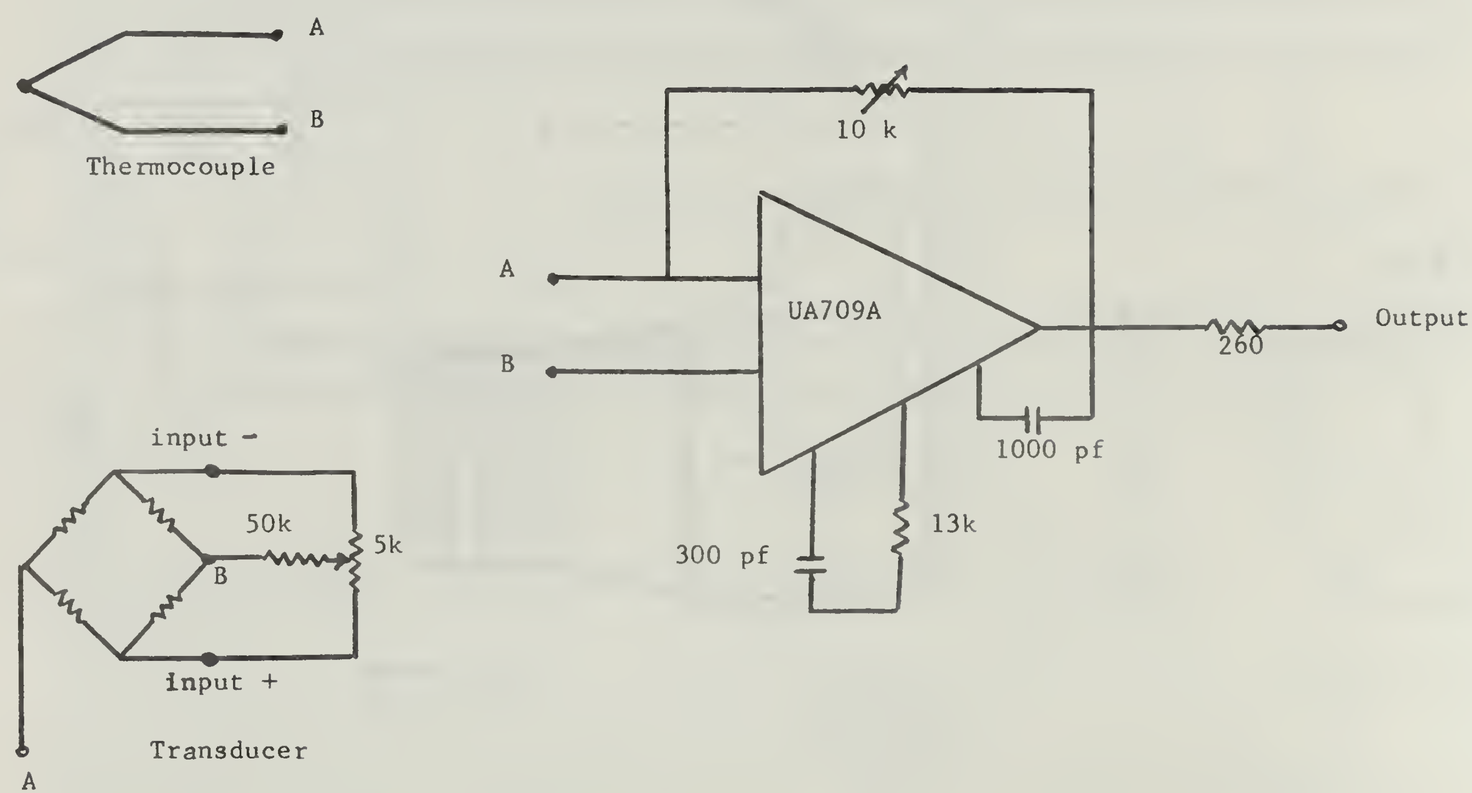

Fig. 14 D C Amplifier Circuit

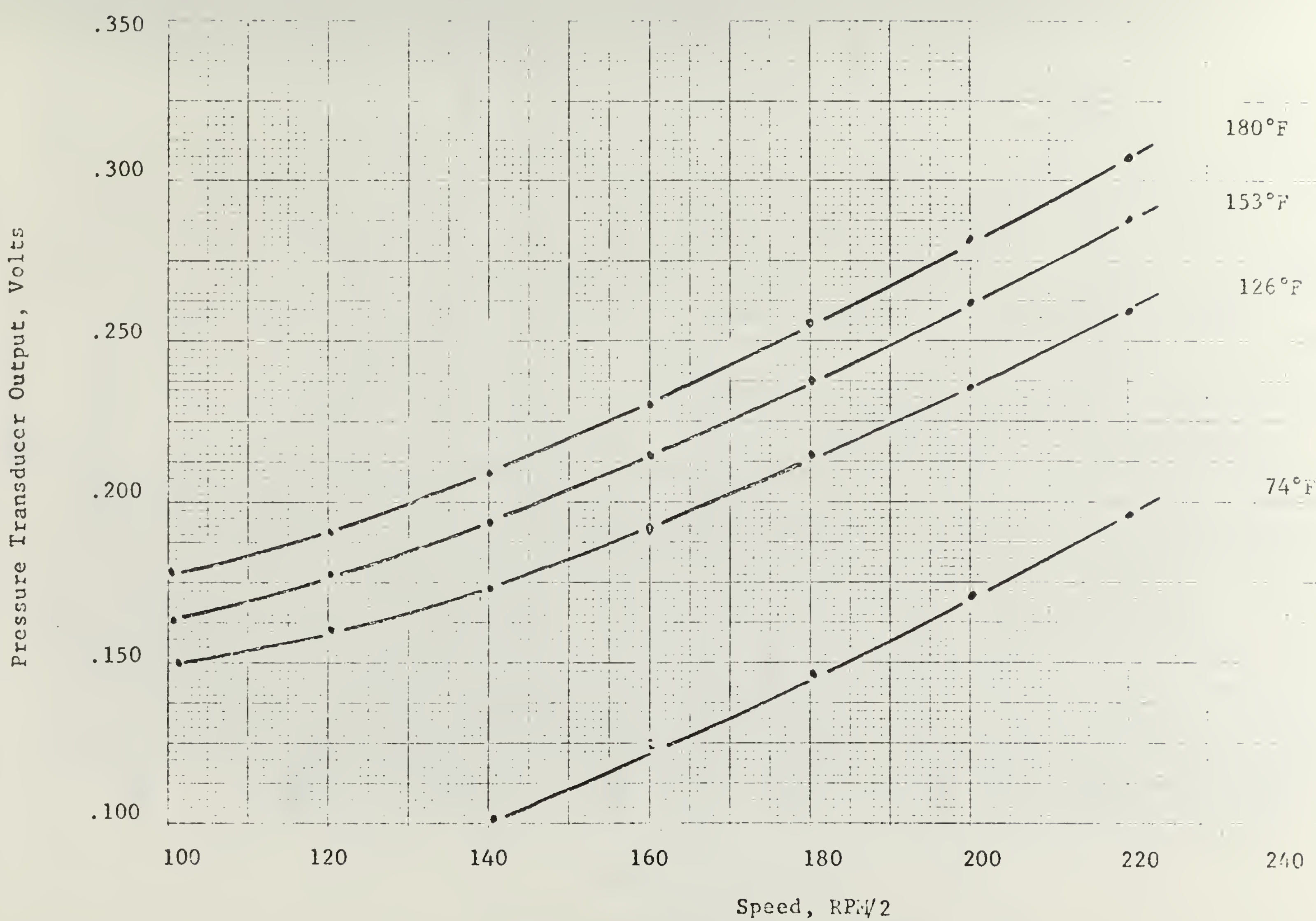

Fig. 15 Pressure Transducer Output vs RPM for Constant Temperature

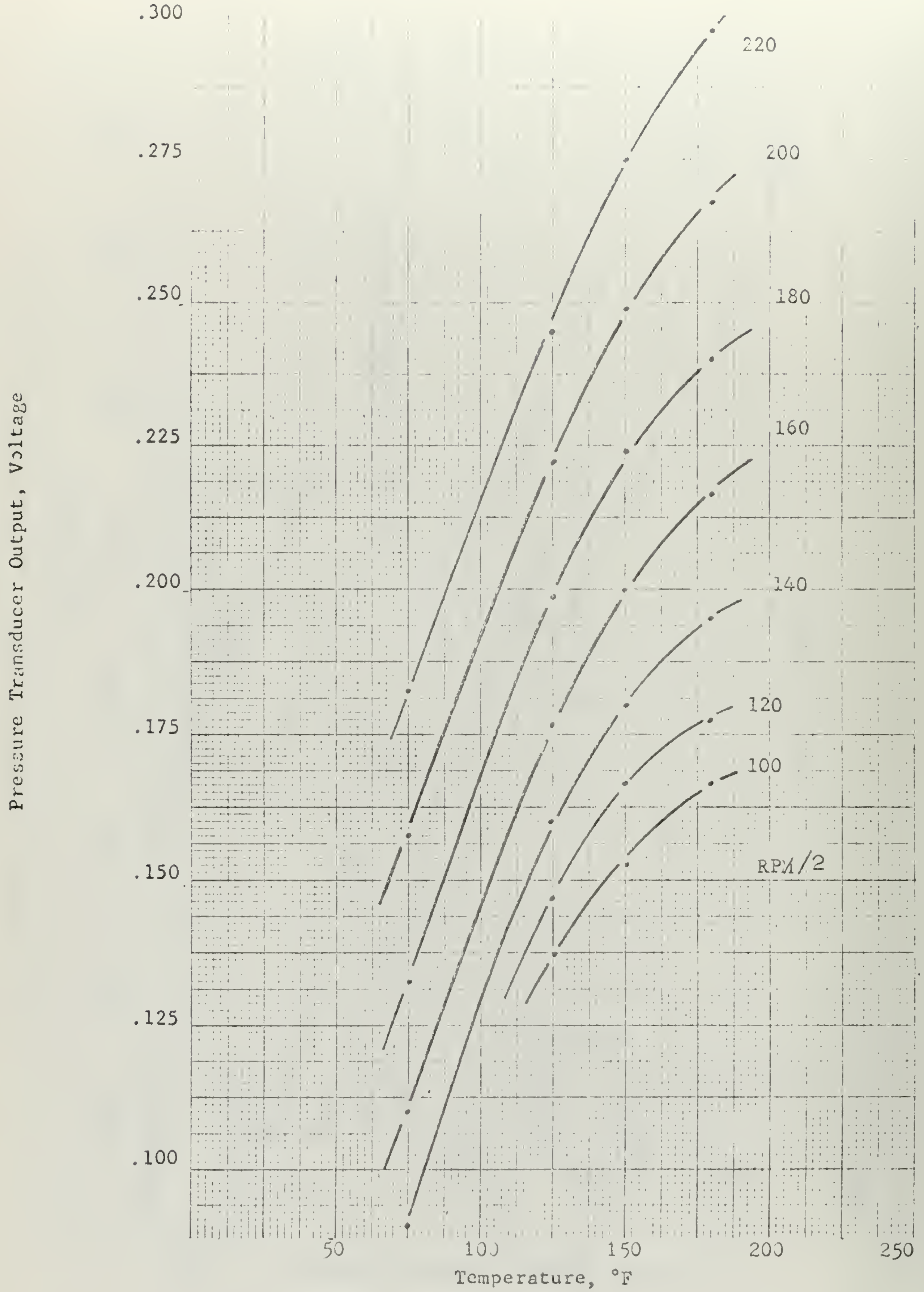

Fig. 16 Pressure Transducer Output vs Temperature at Constant RPM

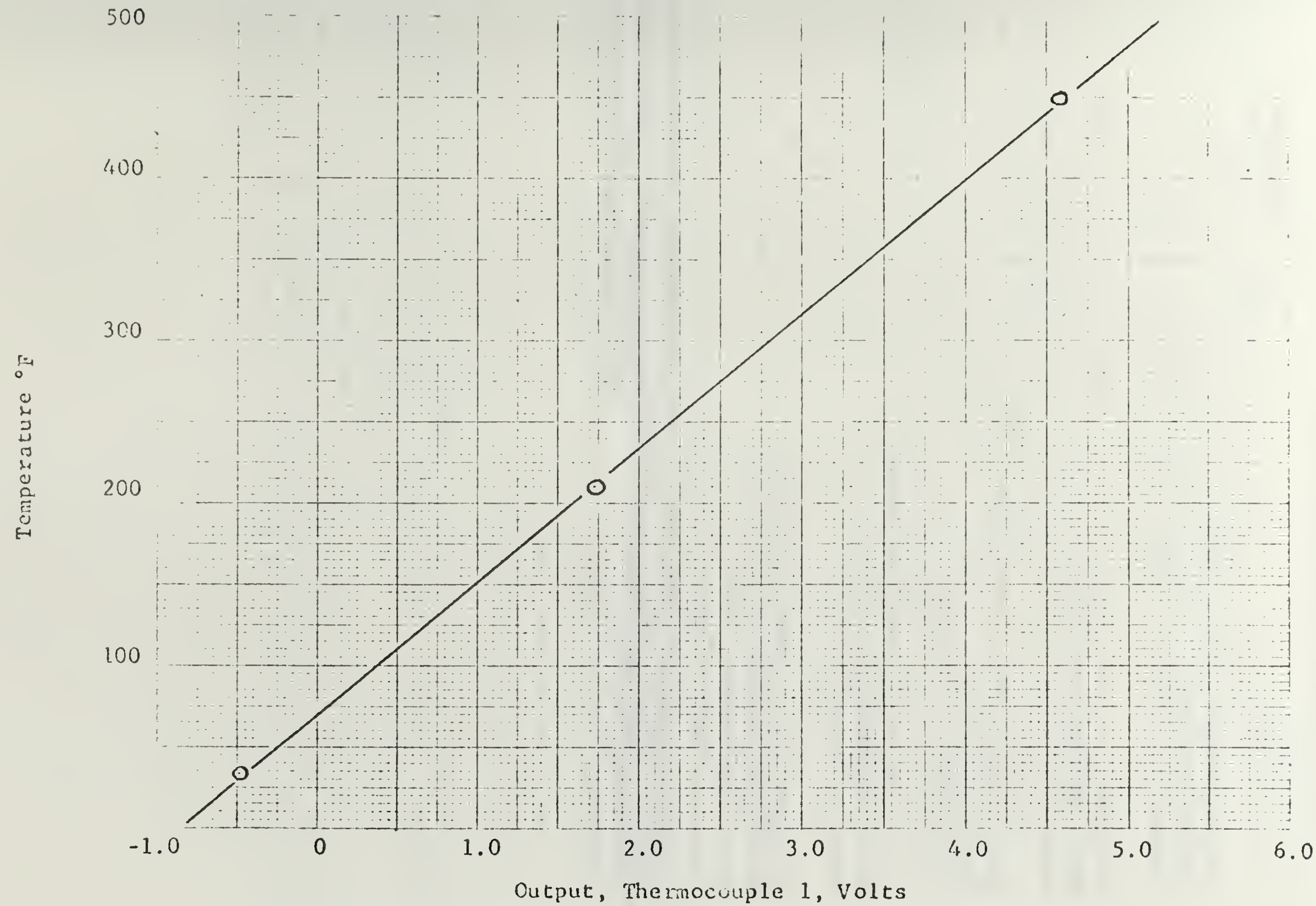

Fig. 17 Sample Temperature-Voltage Curve

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13. ABSTRACT

A centrifuge system was designed and constructed to investigate nucleate pool boiling of water from a mirror finished copper surface. The system was constructed to withstand acceleration force levels up to 1800 g's and to operate at heat fluxes to 200,000 BTU/hr-ft^2.

No nucleate boiling data was taken due to minor experimental difficulties and due to more serious problems that developed with the heater wire and especially with the thermocouple instrumentation. The system was operated to 460 RPM (200 g's) during calibration runs however, and was observed to function well.

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Pool Boiling						
Centrifuge						
Acceleration						
High Gravity						

[redacted]

[redacted]